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Note

Quantification with SPEI of historical droughts and under probable climatic change in the Zacatecas weather station, Mexico

Cuantificación con el SPEI de sequías históricas y bajo cambio climático probable en la estación climatológica Zacatecas, México

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Abstract

The SPEI (Standardized Precipitation-Evapotranspiration Index) is a variant of the widely used SPI (Standardized Precipitation Index). It has greater potential as a drought index since it is sensitive to climate change, given that it uses a more realistic measure of the water availability, namely, the climate balance. This measure is represented by the difference between monthly precipitation and potential evapotranspiration. This study describes in detail the calculation of the SPEI and its application to the monthly historical precipitation and average temperature records available from the Zacatecas weather station, located in the capital of the state of Zacatecas, Mexico. The data covers 86 years over the period 1930 to 2015. For historical droughts, the SPEI results indicate approximate values of 32.2, 11.5, 5.0 and 1.3% for light, moderate, severe and extreme droughts, respectively. For this particular location, three climatic change scenarios were proposed: the first

one adopts a progressive and linear reduction of 20% in annual precipitation; the second one adopts a progressive and linear increase of 4 °C in the average temperature, and the third superimposes the two effects mentioned, which is therefore the most critical. For the three proposed scenarios, the results suggest that light and extreme droughts slightly increase in number or percentage, and that moderate and severe droughts decrease also only slightly. Results are shown with three types of graphs: the SPEI evolution for 12 months, a historical graph, and third clearly show the times of occurrence of drought periods as well as specific differences in the SPEI value. Based on these analyses, a systematic application of the SPEI for the characterization of historical and future droughts is recommended. Its application for future droughts would only be indicative.

Keywords: SPEI index, Log-Logistic distribution, probability weighted moments, potential evapotranspiration, statistical homogeneity, climate change.

Resumen

El SPEI (Standardized Precipitation-Evapotranspiration Index) es una variante del ampliamente difundido SPI (Standardized Precipitation Index), que tiene un mayor potencial como *índice de sequías*, al ser sensitivo al cambio climático, debido a que usa una medida más real de la disponibilidad de agua: el *balance climático*. Esta medida se evalúa con la diferencia entre precipitación y evapotranspiración potencial mensuales. En este estudio se describe con detalle el procedimiento operativo del SPEI y se aplica a los registros históricos mensuales disponibles de precipitación y temperatura media en la estación climatológica Zacatecas, ubicada en la capital del estado de Zacatecas, México, los cuales abarcan 86 años (1930-2015). Para las *sequías históricas*, los resultados del SPEI definen para las sequías leves, moderadas, severas y extremas los siguientes valores aproximados: 32.2, 11.5, 5.0 y 1.3%. Para esta ubicación del país se consideró conveniente formular tres escenarios del *cambio climático*: el primero acepta una reducción progresiva y lineal de 20% en la precipitación anual; el segundo adopta un aumento progresivo y lineal de 4 °C en la temperatura media anual, y el tercero sobrepone los dos efectos citados y, por lo tanto, es el más crítico. En los tres escenarios planteados se encuentra que las sequías leves y extremas aumentan de forma somera en número o porcentaje, y que las sequías moderadas y severas disminuyen también de manera mesurada. Se exponen los gráficos de evolución del SPEI de duración de 12 meses, histórico y del tercer escenario, en los cuales se visualizan con claridad las

épocas de ocurrencia de los periodos de sequía, así como de las diferencias puntuales en el valor del SPEI. Con base en los resultados de estos análisis, se recomienda la aplicación sistemática del SPEI en la caracterización de las sequías históricas y *futuras*. En estas últimas, los resultados tienen sólo un carácter orientativo.

Palabras clave: índice SPEI, distribución Log-logística, momentos de probabilidad ponderada, evapotranspiración potencial, homogeneidad estadística, cambio climático.

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Introduction and objective

Droughts are one of the main natural causes of damage to agriculture, as well as to all economic activities and to the environment. Droughts occur after long periods of low precipitation, and due to their slow evolution, it is difficult to specify their beginning and end, as well as to estimate their magnitude, duration and territorial scope. On the other hand, due to the continual growth in water demand for all uses and the threat of climate change, in recent years the study of droughts has intensified (Mishra & Singh, 2010; Vicente-Serrano, Beguería & López-Moreno, 2010).

Since droughts are a natural phenomenon and threat, their best characterization is carried out using *indicators* that are climatic, hydrological, agricultural and/or socio-economic variables, numerically showing the potential of droughts to produce deficiencies and damages. A *drought index* is a method based on statistical calculations using indicators. It is aimed at quantifying droughts, thereby enabling their comparison among climates and dissimilar hydrological regimes. It also helps in the development of correct and efficient actions to mitigate the negative impacts of droughts (Mishra & Singh, 2010; Fuchs, Svoboda, Wilhite & Hayes, 2014).

Another important aspect of droughts is their character of multiple time scales (*multiscaler*), which is caused by the *delays* that occur in the use of

water in the different hydraulic systems, so that deficiencies in precipitation are first visible in seasonal agriculture, then in irrigation supplies, hydroelectric power generation and other water uses, and finally, in social, economic and environmental impacts. According to the above, droughts are classified as: *meteorological*, *agricultural*, *hydrological* and *socio–economic*. The latter include environmental damage (Pandey, Sharma, Mishra, Singh, & Agarwal, 2008; Vicente-Serrano *et al*., 2010; Fuchs *et al.*, 2014).

Since the end of the last century, drought studies and the development of related warning and monitoring systems have been based on the PDSI (Palmer Drought Severity Index) and the SPI (Standardized Precipitation Index). The former is based on a soil moisture balance (Palmer, 1965; Wells, Goddard, & Hayes, 2004) and the latter on a probabilistic approach to precipitation (McKee, Doesken, & Kleist, 1993; Wu, Svoboda, Hayes, Wilhite, & Wen, 2007). The PDSI has been criticized for not having a multiscalar character with respect to time and complicated calculations, besides not being sufficiently sensitive to induced changes in precipitation and temperature. The SPI has been shown to efficiently use available information, while its main criticism is that it uses only monthly precipitation data, thereby ignoring other indicators of drought, such as temperature and potential evapotranspiration.

Since droughts are a complex and natural phenomenon with widespread impacts, their characterization has recently been sought through indices based on multiple variables. Hao and Singh (2015) describe the various approaches to constructing *multivariate indices*, among the best known are the use of the soil water balance and latent or *hidden variables*. A hidden variable is constructed with a difference or quotient of variables that have great physical significance in droughts, for example, precipitation and potential evapotranspiration, and thus the RDI (Reconnaissance Drought Index) was proposed with the quotient of these variables (Tsakiris & Vangelis, 2005; Campos-Aranda, 2015), and the SPEI (Standardized Precipitation–Evapotranspiration Index) with its difference, which indicates conditions of water deficit or excess. The SPEI is a new drought index proposed by Vicente-Serrano *et al.* (2010) and Beguería, Vicente-Serrano, Reig and Latorre (2014) whose calculation is similar to the SPI. It is multiscalar and sensitive to changes in the historical precipitation and temperature records, according to the expectations presented by climate change in a zone or region. An application of the SPEI with such an approach has been presented by Törnros and Menzel (2014) for a region in the Middle East.

The *objecive* of this study is to describe in detail the operating procedure for the SPEI and to apply it to the available historical precipitation and average

temperature records from the Zacatecas weather station, located in the capital city of Zacatecas, in the state of Zacatecas, Mexico. This registry covers 86 years in the span of 1930 to 2015. Ten durations of drought ranging from 3 to 60 months were processed and three scenarios were analyzed for possible climate change. The first considers a progressive and linear reduction that reaches 20% of the annual precipitation, the second considers a progressive and linear increase that reaches 4°C in the average annual temperature, and the third, the most critical, combines the negative effects of both types of changes. Based on the percentages defined by SPEI for light, moderate, severe and extreme droughts, the results are compared and conclusions are formulated.

Summary of the operational theory

SPEI calculation

The SPI was applied using various *durations k* of droughts, which ranged from 3 to 72 months (Vicente-Serrano *et al*., 2010). The monthly precipitation record was processed using *moving sums*, so that for the duration of 3 months, the first sequence, was obtained by adding historical data one, two and three, the second sequence was the sum of data two, three and four, and so on until the last sequence, which was made up of the antepenultimate, penultimate and the last data. Then the number of *ns* sequences that could be formed depended on *k* and is defined by expression:

$$ns = 12 \cdot \mathrm{NA} - k + 1 \qquad (1)$$

in which NA (for its Spanish initials) is the number of complete years in the processed record (> 30 years). The fundamental difference between the calculation of SPI and SPEI is that the latter uses as historical data the differences ($D_{j,i}$) between monthly precipitation ($P_{j,i}$) and the monthly potential evapotranspiration ($ETP_{j,i}$, for its Spanish initials), that is:

$D_{j,i} = P_{j,i} - ETP_{j,i}$ (2)

Logically, *j* varies from 1 to 12 and *i* from 1 to NA. In order to proceed with the calculation of the SPEI, first, the sequences of differences designated by D_t^k are formed, in which *t* varies from 1 to *ns*. When taking into account that most of the differences D_t^k are negative, there is a need to use a probabilistic model with three fit parameters, whose location parameter *u* is less than the smallest of the sequences to be processed. Vicente-Serrano *et al.* (2010) and Beguería *et al*. (2014) contrasted four distributions: Log–Normal, Pearson type III, Generalized xtreme Value and Log–Logistics; the latter is recommend, fitted with the method of biased weighted probability moments (βs), whose equations are (Stedinger, Vogel, & Foufoula-Georgiou, 1993; Vicente-Serrano *et al.*, 2010):

$$\beta_s = \frac{1}{ns}\sum_{l=1}^{ns}(1-F_l)^s \cdot D_l^k \qquad \text{with} \quad s = 0, 1, 2, \quad (3)$$

being:

$$F_l = \frac{l-0.35}{ns} \qquad (4)$$

In Equation (3), the sequences are in increasing order $\left(D_1^k \le D_2^k \le \cdots \le D_{ns}^k\right)$. Beguería *et al*. (2014) have proposed to use the unbiased βs when biased estimators do not lead to a numerical solution. Stagge, Tallaksen, Gudmundsson, Van Loon, & Stahl (2015) have suggested using the General Extreme Value distribution, fitted with the maximum-likelihood method. The equation for the cumulative probability distribution function [*F* (*x*)] of the Log-Logistic distribution is (Haktanir, 1991):

$$F(x) = \left[1 + \left(\frac{x-u}{\alpha}\right)^{-1/\gamma}\right]^{-1} \qquad (5)$$

where γ > 0, α > 0 and $u < x_{mo}$ are the parameters of form, scale and location and x_{mo} is the minimum sequence observed. The values of the fitting parameters are estimated with the following expressions (Haktanir, 1991):

$$\gamma = 3 - \frac{2 \cdot (\beta_0 - 3 \cdot \beta_2)}{(\beta_0 - 2 \cdot \beta_1)} \qquad (6)$$

$$\alpha = \frac{(\beta_0 - 2 \cdot \beta_1)}{\gamma \cdot \Gamma(1+\gamma) \cdot \Gamma(1-\gamma)} \qquad (7)$$

$$u = \beta_0 - \alpha \cdot \Gamma(1+\gamma) \cdot \Gamma(1-\gamma) \qquad (8)$$

in which Γ (·) is the gamma factorial function, which was estimated with the formula by Stirling (Davis, 1972):

$$\Gamma(\varepsilon) \cong e^{-\varepsilon} \cdot \varepsilon^{\varepsilon - 1/2} \cdot \sqrt{2\pi} \cdot \left(1 + \frac{1}{12 \cdot \varepsilon} + \frac{1}{288 \cdot \varepsilon^2} - \frac{139}{51840 \cdot \varepsilon^3} - \frac{571}{2488320 \cdot \varepsilon^4} + \cdots\right) \qquad (9)$$

After calculating the three fit parameters (γ, α, u) for each duration *k* analyzed, Equation (5) is applied with x = D_t^k to estimate the non–exceedance probabilities *F*(*x*) corresponding to each difference. Then, the rational numerical approximation is used, developed by Zelen and Severo (1972) and presented by Campos-Aranda (2015), to convert *F*(*x*) into the standardized normal variable Z of zero mean and unit variance, which corresponds to SPEI. Light, moderate, severe and extreme droughts are defined when the SPEI ranges from 0 to –1.00, from –1.00 to –1.50, from –1.50 to –2.00 and when it is less than –2.00, respectively.

Monthly *ETP* calculation

Mavromatis (2007) found that the use of simple or complex methods for estimating $ETP_{j,i}$ leads to similar results when applying drought indices such as that of Palmer. Based on this result, Vicente-Serrano *et al*. (2010) adopted a simple approach to estimate the $ETP_{j,i}$, through the Thornthwaite formula, whose expression is:

$$ETP_{j,i} = 16 \cdot Fc \cdot \left(\frac{10 \cdot Tt_{j,i}}{IC_i} \right)^m \qquad (10)$$

in which *Fc* is a correction factor function for the latitude of place (LAT) and number of days in the month (*ndm*). Its formula is:

$$Fc = \left(\frac{N}{12} \right) \cdot \left(\frac{ndm}{30} \right) \qquad (11)$$

where *N* is the maximum sunshine or maximum number of hours with average monthly sun. For its estimation in the Mexican Republic, Campos-Aranda (2005) developed the following empirical expression:

$$N = A + B\,[\text{sen}\,(30\,nm + 83.5)] \qquad (12)$$

where *nm* is the number of month, with 1 for January and 12 for December; *A* and *B* are constant functions of LAT in degrees, with the following expressions:

$$A = 12.09086 + 0.00266 \cdot \text{LAT} \qquad (13)$$

$$B = 0.2194 - 0.06988 \cdot \text{LAT} \qquad (14)$$

$Tt_{j,i}$ is the average monthly temperature in °C and IC_i is an annual heat index, equal to the sum of the 12 monthly indices, which are:

$$icm = \left(\frac{Tt_{j,i}}{5} \right)^{1.514} \qquad (15)$$

Finally, the exponent *m* is a function of IC_i with the following empirical equation:

$$m = 6.75 \cdot 10^{-7} \cdot IC_i^3 - 7.71 \cdot 10^{-5} \cdot IC_i^2 + 1.792 \cdot 10^{-2} \cdot IC_i + 0.4924 \qquad (16)$$

For values of $Tt_{j,i}$ that are higher than 26.5 °C, there is no influence from IC_i, so $ETP_{j,i}$ is only a function of $Tt_{j,i}$ and is tabulated by Campos-Aranda (2005).

Hypothetical scenarios of climate change

Vicente-Serrano *et al.* (2010) and Ma *et al*. (2014) have suggested that at least two scenarios must be studied as a consequence of climate change processes. One is a reduction in precipitation and the other is an increase in average temperature. Based on quantitative analyses done by these authors and the climatic projections for Mexico by Montero, Martínez, Castillo and Espinoza (2010), three scenarios were established for analysis: (1) a progressive and linear reduction of 20% in the annual precipitation recorded by the historical registry; (2) a progressive and linear increase of 4 °C in the average annual recorded temperature and (3) the superimposition of both changes in the historical record. The changes mentioned have a direct impact on the severity and duration of droughts (Fuchs *et al*., 2014). The correction of the monthly precipitation record ($PM_{j,i}$) is made based on the following equation:

$$PM_{j,i} = PM_{j,i} - (\Delta_P \cdot i \cdot PM_{j,i}) \qquad (17)$$

in which Δ_P is the slope of the reduction and therefore equals the quotient of 0.20 divided by the number of years NA, and *i* is the year counter, ranging from 1 to NA. The average monthly temperature correction (TM_{ij}) is carried out with equation:

$$TM_{j,i} = TM_{j,i} + (\Delta_T \cdot i) \qquad (18)$$

where Δ_T is the slope of the increase and therefore equal to the quotient of 4 °C divided by NA.

Processed data and their results

Historical records available

The Zacatecas weather station is located in the city of Zacatecas, which is the capital of the state of Zacatecas, Mexico, and which according to historical information provided by the Local Office of the National Water Commission (Conagua) has operated continuously and has not changed location, so the records can be considered reliable. Its geographical coordinates are as follows: latitude 22° 45' N, longitude 102° 34' W and altitude 2485 m.a.s.l. Its available monthly precipitation (mm) records and average temperature (°C), stored in Excel files by CONAGUA of Zacatecas, started in January 1953 and are available until December 2015, with missing data in April 1986 and several months during the years 2010 to 2013.

The first missing data were considered equal to the monthly averages and the rest was considered equal to the values recorded during the same months in the Guadalupe weather station, which is approximately 6 km away in a straight line and is located inside the same geographical sub-region. This was considered acceptable due to the similarity that both records showed at the annual level, both in precipitation and in average temperature. On the other hand, in the Climatological Bulletin No. 3 (SARH, 1980) of the Hydrological Region No. 37 (El Salado), the available records from the Zacatecas station for the monthly precipitation and average temperature begin in January of 1930 and go up to December of 1978. Then, the period from January 1930 to December 1952, without missing data, was taken from this Bulletin and with it a joint record of NA = 86 years was created. The twelve monthly average values for the integrated precipitation record are: 16.2, 9.6, 5.7, 7.5, 17.7, 80.0, 102.1, 97.9, 85.4, 35.4, 12.8 and 12.0, whose sum is 482.2 mm, which corresponds to the average annual precipitation. The average monthly temperatures recorded are: 11.7, 12.7, 14.8, 17.1, 19.0, 19.0, 17.5, 17.6, 17.0, 16.1, 14.1 and 12.3, with an annual average value of 15.7 °C.

Homogeneity tests of historical records

Starting with the monthly historical records, the annual values for precipitation and average temperature were integrated, to which three basic tests (Helmert, Sequences and Von Neumann) and six specific tests were applied: two of persistence (Anderson and Sneyers), two of trend (Kendall and Spearman), one of them of change in variability (Bartlett) and another of change in the mean, that of Cramer. These tests can be consulted in WMO (1971); Campos-Aranda (2005), and Machiwal and Jha (2012).

The annual precipitation record is perfectly homogeneous, since no general or specific test detected any deterministic components. On the other hand, the mean annual temperature record was not homogeneous given that the basic and specific tests indicated persistence and change in mean. This evidence of lack of homogeneity justifies the approach of scenarios related to climate change.

Results from the SPEI with the historical records

For this study, it was decided to analyze the following ten durations *k* of droughts: 3, 6, 9, 12, 18, 24, 30, 36, 48 and 60 months. In Table 1, the results obtained with available historical records are shown for each duration according to four concepts: (1) those related to the statistical properties of the sequences formed, (2) those corresponding to the fitting of the Log-Logistics distribution, (3) those associated with the statistical SPEI indicators and (4) those belonging to the drought types that were defined.

The first group of results provides an idea of the variability and bias of the sequences formed with the criterion of moving sums, in such a way that the second group, which is the fit parameters of the distribution, is related to this behavior. The third group of results is the most important, because it defines the quality of the fit obtained and therefore the reliability of the estimates made with the SPEI, since its mean, variance and percentage of droughts that it defines should be zero, the unit and 50%, respectively. As such indicators approximate the values cited, the estimate will be better or more reliable.

As Table 2 shows, the most accurate estimates were those having durations of 12, 24 and 36 months, defining approximate percentages of 32.2, 11.5, 5.0 and 1.3 corresponding to light, moderate, severe and extreme droughts, respectively. Figure 1a shows the historical evolution of SPEI with a duration of 12 months, observing that wet and dry periods alternate. The longest

drought began around sequence 153 (September 1941) and ended in 416 (August 1963). The date corresponding to a sequence is obtained by clearing from Equation (1) the value of NA in years, which is added to the initial year of the record. During this period, the most extreme SPEI occurs, with –2.742 in sequence 321 (October 1954).

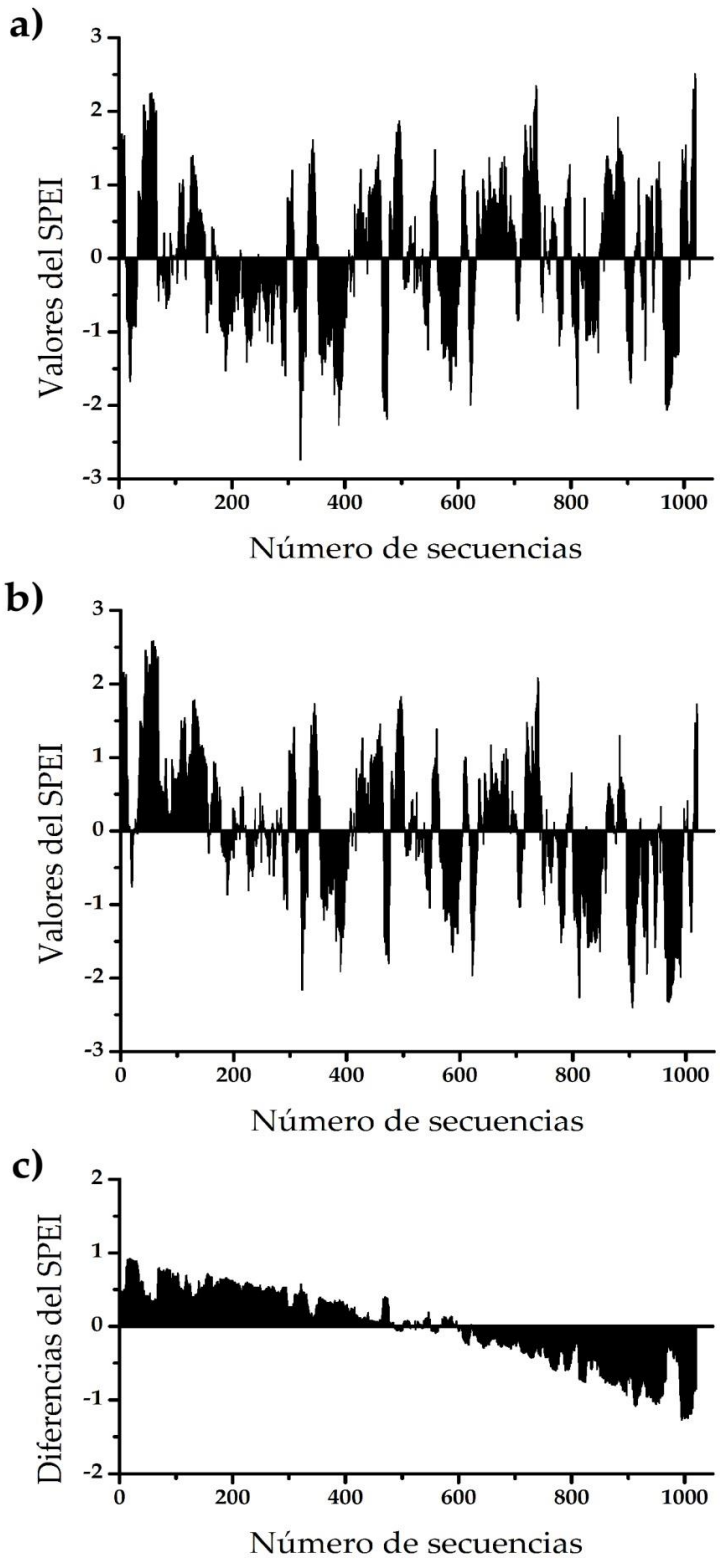
a)
Valores del SPEI
Número de secuencias
b)
Valores del SPEI
Número de secuencias
c)
Diferencias del SPEI
Número de secuencias

Figure 1. (a) SPEI evolution of 12 months duration in the Zacatecas weather station, state of Zacatecas, Mexico; (b) SPEI evolution (k = 12 months) with reduction of 20% in the annual precipitation and increase of 4 °C in the average annual temperature and (c) Differences between the SPEI shown (b – c).

SPEI results with modified climate records

Based on Equations (17) and (18), the historical records were modified to incorporate a progressive and linear decrease of 20% in annual precipitation and a progressive and linear increase of 4 °C in the average annual temperature. Table 2 shows various relevant values for the historical records and those for the modified records, according to possible climate change, as well as the annual *ETP* values estimated with the Thornthwaite method.

Table 1. Characteristic values of the historical climatic records and their hypothetical versions according to the probable climate change, in the Zacatecas weather station, Mexico.

Annual record of:	**historical value**		**minimum**		**maximum**		**average value**
	inicial	**final**	**valor**	**año**	**valor**	**año**	
Historical precipitation (mm)	630.9	1019.0	169.3	1969	1019.0	2015	482.2
Average temperature (°C)	15.2	16.2	14.2	1985	16.8	1962	15.7
ETP (mm) with the Thornthwaite (THW) method	736.6	763.9	704.7	1985	792.9	1962	752.8
Precipitation with progressive reduction of 20% (mm)	629.4	815.2	145.3	2011	880.9	1935	432.9
Average temperature with progressive increase to 4°C	15.2	20.2	15.1	1931	20.4	2006	17.8
ETP (mm) of THW and average temperature with increase	738.1	950.7	735.5	1931	975.3	2006	833.6

Similar to Table 2, in Table 3 the SPEI results from the record modified according to the third scenario are presented, *i.e.*, considering the combined effect of both changes. Due to space limitation the results of the SPEI with a reduction in precipitation and with an increase in average temperature are not shown, but they are available from the author. Based on all the SPEI results, the duration of 24 months was defined as the ideal for the contrast between the values obtained with the historical registry and the modified one. This contrast is shown in Table 4.

Table 2. SPEI results from the monthly historical data from the Zacatecas weather station, Mexico.

Numerical concepts:	Duration in months of the analyzed sequences									
	3	6	9	12	18	24	30	36	48	60
Of sequences										
Number of sequences	1030	1027	1024	1021	1015	1009	1003	997	985	973
Minimum moving sum	–255.0	–389.6	–513.3	–668.6	–867.1	–1059.0	–1322.5	–1487.3	–1923.4	–2214.9
Maximum moving sum	385.4	398.7	352.1	284.2	429.7	295.2	310.5	43.8	–276.6	–373.2
Arithmetic mean	–67.6	–135.4	–203.9	–273.1	–412.9	–552.7	–692.2	–832.2	–1110.7	–1389.4
Standard deviation	100.2	135.0	150.4	156.4	214.5	234.5	278.2	289.4	337.9	380.6
Asymmetry coefficient	1.000	0.799	0.640	0.548	0.525	0.539	0.546	0.451	0.234	0.145
Of the FDP										

(LL3)										
Shape parameter (γ)	0.170	0.148	0.109	0.097	0.080	0.090	0.090	0.084	0.063	0.043
Scale parameter (α)	306.080	488.254	756.282	892.865	1488.127	1436.100	1701.987	1910.519	3054.045	5010.527
Location parameter (*u*)	–388.266	–641.009	–974.253	–1178.795	–1915.196	–2006.586	–2415.228	–2763.020	–4181.373	–6410.325
Of SPEI										
Arithmetic mean	–0.0008	–0.0006	–0.0033	–0.0042	–0.0061	–0.0049	–0.0050	–0.0053	–0.0070	–0.0114
Variance	0.9994	0.9939	0.9956	0.9987	0.9966	0.9979	0.9980	1.0011	1.0079	1.0154
Minimum value	–2.438	–2.287	–2.311	–2.742	–2.247	–2.334	–2.445	–2.405	–2.408	–2.134
Number of negative values	539	519	524	517	496	508	510	504	501	481
% of droughts	52.3	50.5	51.2	50.6	48.9	50.3	50.8	50.6	50.9	49.4
Of the types of droughts										
% of light droughts	36.2	32.0	33.5	32.8	29.4	32.0	33.6	33.0	29.7	27.9
% of moderate droughts	8.5	12.2	10.6	11.8	13.3	11.3	10.7	11.4	17.5	17.6
% of severe	6.0	5.6	5.8	4.8	5.2	5.7	4.9	4.2	2.1	3.3

droughts										
% of extreme droughts	1.6	0.8	1.3	1.3	1.0	1.3	1.7	1.9	1.5	0.7

Table 3. SPEI results from the monthly modified records with combined effects (reduction in precipitation and increase in average temperature), in the Zacatecas weather station, Mexico.

Numerical concepts:	Duration in months of the sequences analyzed									
	3	6	9	12	18	24	30	36	48	60
Of sequences										
Number of sequences	1030	1027	1024	1021	1015	1009	1003	997	985	973
Minimum moving sum	–324.9	–474.3	–632.2	–766.5	–1143.5	–1409.6	–1827.0	–2035.6	–2487.3	–2994.2
Maximum moving sum	374.1	382.3	278.9	165.0.	395.9	259.6	265.5	–4.2	–347.8	–433.3
Arithmetic mean	–100.2	–200.4	–301.1	–402.3	–606.4	–810.2	–1013.7	–1217.2	–1622.9	–2029.6
Standard deviation	92.8	127.1	147.8	161.3	225.3	261.8	315.6	349.8	435.1	510.2
Asymmetry coefficient	0.858	0.799	0.658	0.586	0.671	0.663	0.639	0.596	0.542	0.590
Of the FDP										

(LL3)										
Shape parameter (γ)	0.111	0.115	0.090	0.076	0.084	0.078	0.074	0.070	0.086	0.104
Scale parameter (α)	445.425	594.791	892.728	1164.482	1462.824	1816.866	2324.999	2725.995	2784.609	2683.450
Location parameter (*u*)	–554.178	–807.591	–1204.922	–1576.584	–2084.635	–2643.534	–3357.198	–3962.384	–4438.525	–4758.173
Of SPEI										
Arithmetic mean	–0.0053	–0.0041	–0.0062	–0.0081	–0.0070	–0.0080	–0.0085	–0.0091	–0.0061	–0.0045
Variance	1.0015	0.9958	0.9968	0.9991	0.9989	0.9988	0.9990	0.9999	1.0001	1.0005
Minimum value	–2.810	–2.486	–2.444	–2.401	–2.569	–2.453	–2.700	–2.456	–2.154	–2.113
Number of negative values	521	516	498	500	509	499	510	500	484	497
% of droughts	50.6	50.2	48.6	49.0	50.1	49.5	50.8	50.2	49.1	51.1
Of the types of droughts										
% of light droughts	34.3	33.6	29.7	30.4	33.1	32.3	33.1	32.1	30.8	31.3
% of moderate droughts	8.7	9.6	12.0	11.4	9.9	10.9	10.1	9.8	10.2	12.1
% of severe	4.9	5.6	5.4	5.3	5.0	4.5	6.2	7.1	7.2	7.3

droughts										
% of extreme droughts	2.7	1.4	1.6	2.0	2.1	1.8	1.5	1.1	1.0	0.3

Table 4. Number of events and percentages of each drought type obtained with an SPEI of 24 months duration from the historical records (Table 2) and their contrast with the ones modified according to probable climate change.

Types of drought and minimum value of SPEI	**Table 2**	**Reduction in precipitation**	**Increase in temperature**	**Table 3 Combined effects**
Light	323 (32.0%)	357 (35.4%) >	356 (35.3%) >	326 (32.3%) >
Moderate	114 (11.3%)	90 (8.9%) <	88 (8.7%) <	110 (10.9%) <
Severe	58 (5.7%)	53 (5.3%) <	60 (5.9%) >	45 (4.5%) <
Extreme	13 (1.3%)	21 (2.1%) >	18 (1.8%) >	18 (1.8%) >
SPEI	−2.334	−2.401	−2.547	−2.453

The results shown in Table 4 indicate that, in general, light and extreme droughts will increase as a result of probable climate change; in contrast, moderate and severe droughts will decrease. These results show an anomaly in severe droughts corresponding to the record with an increase in temperature, which also increases. Regarding the extreme SPEI values, they are considered to be in agreement with the modifications applied to the historical records. For the third scenario, the most critical, this is shown in Table 3 as having more accurate results than those of the 18-month duration, with the following percentages for the four types of droughts sought: 33.1, 9.9, 5.0 and 2.1.

Figure 1b shows the evolution of the SPEI for a 12-month duration with the record that includes both effects of climate change. It is clear how droughts will increase in duration and severity towards the end of the record, significantly reducing wet periods. Finally, Figure 1c shows the SPEI differences of Figure 1b minus 1a.

Conclusions

The results from the SPEI based on the historical records from the Zacatecas weather station (Table 2), located in the capital of Zacatecas, in the state of Zacatecas, Mexico, define approximately 32.2%, 11.5%, 5.0% and 1.3% for light, moderate, severe and extreme droughts, respectively. These percentages and the following ones were obtained based on drought durations of 12 to 30 months.

In the three climate change scenarios, light and extreme droughts were generally found to increase briefly and moderate and severe droughts decrease, also slightly in number or percentage. They are defined globally for the third scenario (Table 3), the most critical, for combined precipitation reduction and average temperature increase, as 32.7%, 10.5%, 4.8% and 2.0% for each type of drought.

The evolution graphs of the SPEI, as shown in Figure 1 for a 12-month drought duration, allow for accurate visualization and definition of drought periods as well as maximum or extreme point values, with respect to both the historical record and the records modified according to probable climatic change.

Taking into account the consistency of the results of this study, the systematic application of SPEI to the quantification of historical and future droughts is recommended, the former based on available historical records and the latter on their modified versions, which must consider the possible effects of climate change in each zone or region of the country.

For the climate change scenarios that are considered feasible to occur, SPEI results can help to put into perspective the impact on the water balance of a region. However, being uncertain how exactly droughts will evolve in the future, the SPEI results can only be considered as guidelines.

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